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PROFILES IN SCIENCE

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Ultrasonic Telemetry of Shark Behavior

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Biotelemetry is a relatively new technique particularly applicable to monitoring the behavior of sharks in the natural environment, and is providing important information previously unavailable to scientists. With data received from transmitters attached to free-ranging individuals, it is now possible to "observe" and analyze aspects of shark behavior impossible to study by other methods. For several years, under Office of Naval Research support, the shark-behavior research program at California State University has devoted effort to the development of an effective telemetry system for sharks, and to the utilization of this system for behavioral studies of sharks at sea. Long Beach has proven an advantageous home base for this project because of the ready availability of sharks offshore, and also because of the proximity of materials and technical knowhow at nearby aerospace/hydrospace/electronics industries and Naval installations.

Navy Interest in Sharks

The primary interest of the U.S. Navy in shark research is to develop means of coping with the shark hazard to men and equipment in the sea, particularly for Naval personnel under survival conditions or during swimmer/diver operations. Baldridge and Johnson (1) reviewed the various antishark devices and procedures available, and emphasized the importance of the use of "good shark sense" and that knowledge about these animals is "without a doubt our most valuable weapon against shark attack." With this rationale, the Office of Naval Research is supporting basic research on the behavior of sharks in the wild. Information obtained is used not only to develop more effective antishark hardware, but to provide better advice to personnel on how to avoid or minimize the risk from encounters with dangerous sharks.

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As a result of more than a decade of investigation, most of it Navy supported, scientists have learned much about the sensory capacities of sharks, e.g., visual, acoustic, chemical, electric, and this information has clearly furthered our understanding of shark attacks. From studies of both captive individuals and free-ranging "attracted" individuals we also know how sharks behave in response to certain kinds of stimuli. However, for most species, we know very little about natural behavior *per se*. For example, we are only now beginning (via telemetry) to learn something about the daily behavioral routines of active sharks in the wild. For the large, dangerous species we know almost nothing about social structure, aggression, territoriality, or courtship. These aspects of behavior are especially relevant in view of recent evidences that many, if not most, shark attacks are non-feeding motivated (2,3). This lack of information is really why sharks have been so often labelled "unpredictible," when actually there is no good evidence that sharks behave differently than other animals under a given set of conditions.

Difficulties with Direct Observation

A great deal could be learned if sharks could be unobtrusively observed in their natural habitat for long periods of time. Direct observation is a standard technique for behavioral study of terrestrial species, where effective concealment and long viewing distances are possible, or where the subjects have become sufficiently accustomed to the observer to permit his close proximity. For many animals, such observational study has elucidated more or less the entire behavioral repertoire of the species. By comparison, direct diver observation of sharks in the wild has thus far yielded relatively little behavioral information.

With even the best aquatic visibility very limited (compared to air), active sharks are seldom seen underwater unless attracted within visual range by stimuli such as scent or sound. What is then observed is the shark's response to an atypical, opportunistic feeding situation, further influenced by the usually quite obvious presence of the observer.

Generally, most active sharks avoid divers, especially divers using open-circuit scuba. There are some non-feeding situations where sharks approach divers for apparently investigative reasons (3), but here again, what is usually observed is the shark's response to an atypical stimulus, the diver himself.

Even if a shark were to become totally accustomed to a diver, it is unlikely that he would be able to keep such a wide-ranging animal in view for very long, even in the clearest water. Another problem is that many species of sharks spend much of their time at depths too great for scuba observation. Yet another difficulty is that most sharks are primarily night-active, and many of their interesting behavioral responses probably occur under the cover of darkness.

The Potential of Telemetry

There is clearly a need for more information on how sharks run their daily lives when free of the influence of human observers and other atypical stimuli. Telemetry is of particular value for this type of research, because most sharks are secretive, wide-ranging, and live in a concealing environment.

When telemetering from sharks, the researcher has the advantage that transmitter size is not as critical a limiting factor as it is when working with smaller animals. Shark transmitters can be relatively powerful (large battery) and still have room for much sophisticated circuitry and sensors. With such units, it is now possible to monitor, day and night, multiple aspects of a shark's behavior as it moves through its normal daily routine. With today's techniques of electronic micro-miniaturization, the capabilities of the transmitter and the kinds of information it can telemeter, are limited virtually only by cost and by the ingenuity of the designer.

Attaching a transmitter to a shark can serve two distinct purposes: (a) to telemeter the information desired, (location, depth, swim speed, etc.) and (b) to facilitate locating the shark at any time so that other observations or experiments can then be performed. In regard to the latter purpose, while prolonged observations may turn out to be difficult or impossible, even brief visual contacts with the telemetered shark can yield important data, such as, group size and structure.

Previous Shark Telemetry

Early ultrasonic trackings of aquatic animals utilized relatively simple transmitters which served only as acoustic beacons. Bass and Rascovich (4) established the feasibility of tracking large, fast-swimming fish from a moving vessel at sea. Using relatively large, powerful "pingers" (38 KHz), they tracked one sandbar shark, one

hammerhead shark, and several bluefin tuna for periods of up to four hours. Thorsen (5), using smaller, long-life ultrasonic tags (74 KHz) and several strategically placed shore monitors, confirmed the movements of bull sharks from the Caribbean Sea to Lake Nicarauga via the San Juan River. His units provided only locational information, but could be set at various fixed pulse rates so that individual sharks could be recognized. Although conventional tagging and recapture data also confirmed river traverse, the telemetry method provided more detailed data on rates of movement.

Only recently have researchers employed ultrasonic telemetry to acquire data other than the animal's location. Carey and Lawson (6) used dual-channel temperature sensing transmitters (21 KHz) to measure surface and deep body temperatures of free-swimming tunas, and also for one dusky shark which they tracked for six hours. Kotchabhakdi *et al* (7) used acoustic telemetry to transmit the electrical activity from the brain of free-swimming dogfish sharks.

Multichannel Studies

The initial ONR-supported development work at Long Beach was aimed at producing a practical system for telemetering several aspects of the behavior of free-ranging sharks at sea. In contrast to the much simpler and sometimes smaller units used previously for fish tracking studies, this objective required a relatively powerful, complex transmitter incorporating several sensors and associated switching components. Standora (8,9) described the multichannel transmitter developed at Long Beach, and its initial use in 1971-72 for monitoring the day-night behavior patterns of the Pacific angel shark at Santa Catalina Island, California. His transmitters incorporated sensors for measuring depth, swim speed, light, and temperature; the multiplexed data was tape-recorded for later manual decoding. Nine angel sharks were underwater-tagged (via barbed dart) and subsequently tracked from a boat for periods of from 13 to 25 hours. The sharks were nocturnal in activity, made depth excursions from 90 to over 330 feet, and confined their movements to home ranges covering about one-half square mile.

Sciarrotta (10), using an improved version of the above multichannel transmitter, studied the blue shark (Figures 1,2,3), a dangerous species abundant in offshore temperate waters. Units containing various combinations of depth, temperature, swim speed, and compass-heading sensors were externally applied to free-swimming sharks baited to the boat several miles off Santa Catalina Island.

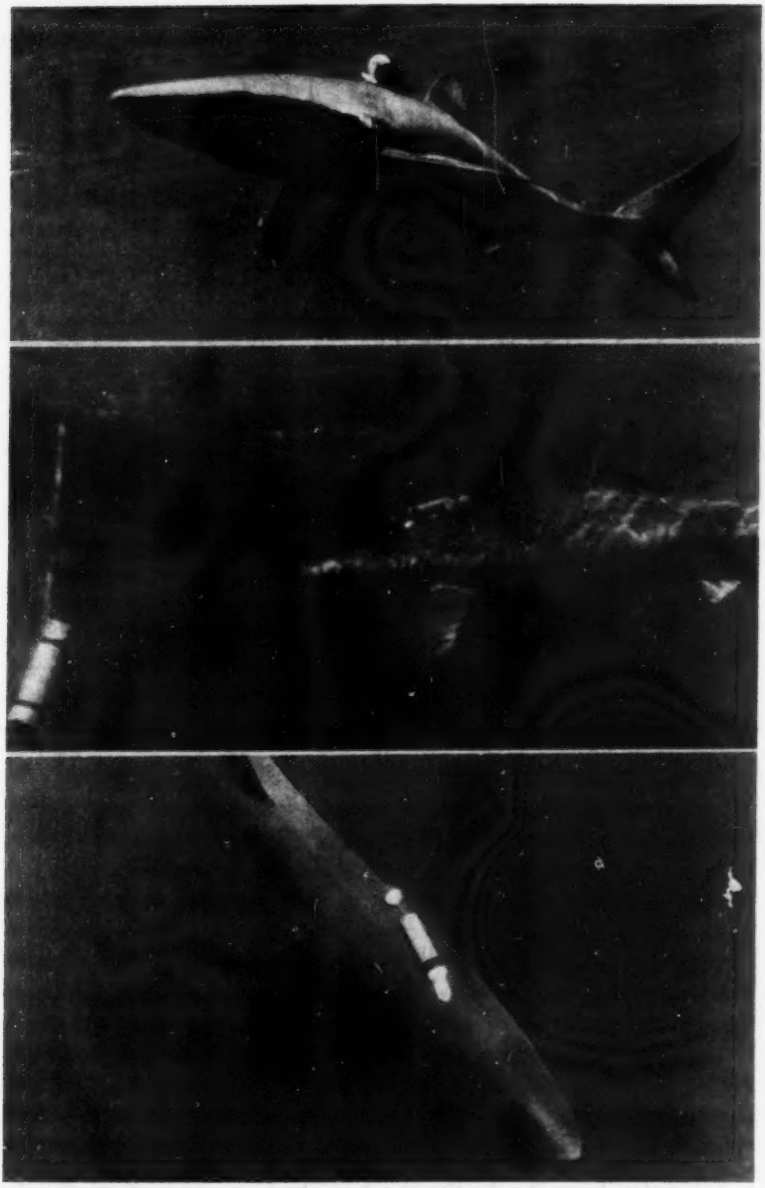

Figure 1—Blue sharks, Prionace glauca, *tagged with Mark III multichannel transmitters with drogue-type speed sensors. Center photo shows large individual, about eight feel long, returning to the bait cannister immediately after tag application (photos by T. Sciarrotta).*

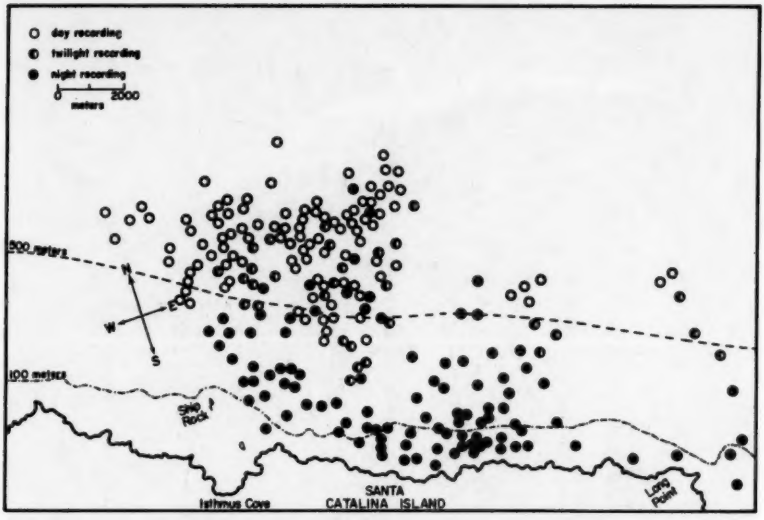

Figure 2–Positions of seven blue sharks tracked by T. Sciarrotta during the spring season of 1972. Note that all day positions are well away from the island, while the majority of night positions are nearshore, often in relatively shallow water. Nocturnal island-oriented movement may be a feeding response to the availability of nearshore prey such as squid.

Telemetered data showed that the sharks were generally more active at night than during the day, with swim speed, rate-of-change of direction, and rate-of-change of depth all greater at night. The most interesting behavior discovered was a well-oriented shoreward migration to the island at dusk. The sharks typically stayed near the island for several hours, then gradually moved back out to sea. Deviation from straight-line swimming increased suddenly upon the early evening arrival at the island, and it was postulated that feeding may occur at this time.

The Present Shark-Telemetry System

Transmitters and Sensors

Telemetry from the depths at which sharks occur is practical only by acoustic transmission, as radio waves are severly attenuated by sea water. The present Mark III and Mark IV single/multichannel units transmit 40 KHz ultrasonic pulses (tone bursts) of 10 msec duration,

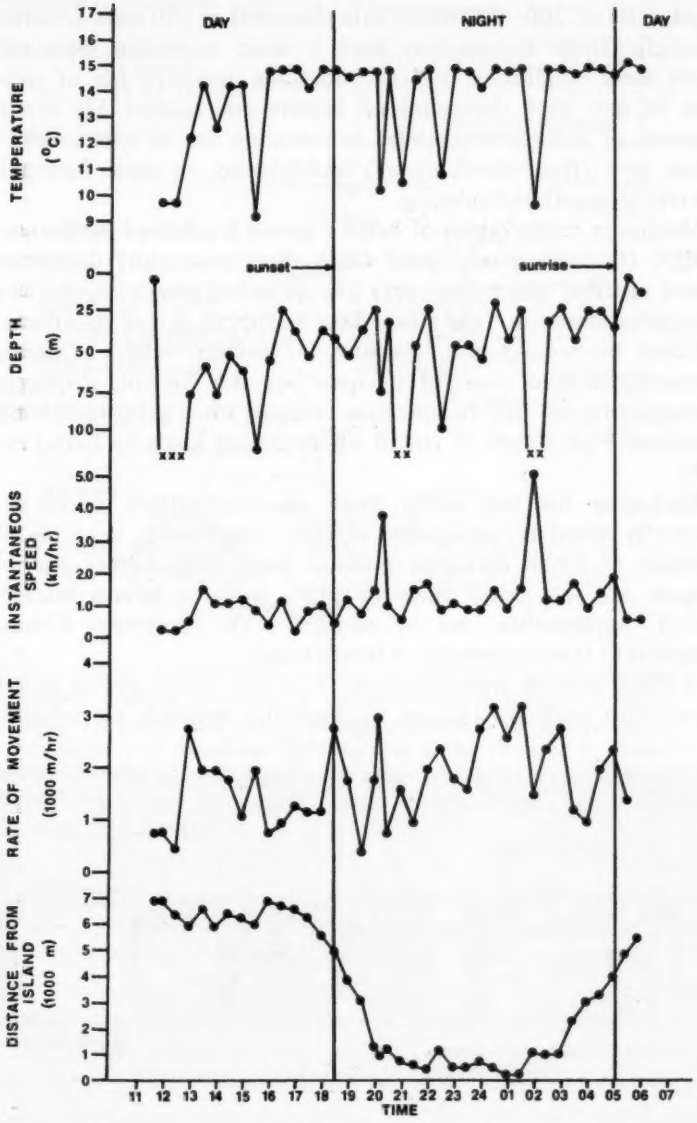

Figure 3–Multichannel data from a blue shark. Note the deep plunge after tag application (x = beyond sensor maximum), the depth-temperature correlations, the peak swim speeds at night, and the close approach to the island in early evening. Data sampled at 30-minute intervals for 18 hours.

at intervals of 200–400 msec (data channels) or 150 msec (reference channel). These transmitters have a range exceeding three miles under ideal conditions, and a continuous operating life of several days to one week depending on battery and sensors. Up to eight channels of pulse-interval-coded information can be telemetered by either slow (fixed-time/channel) multiplexing, or rapid (one-pulse-interval/channel) multiplexing.

Maximum conservation of battery power is achieved by the use of C/MOS (Complimentary/Metal Oxide Semiconductor) digital integrated circuits, which have very low quiescent power requirements. Interpulse duration (and thus data accuracy) is not significantly affected by temperature, pressure, or battery voltage. Operating frequency is held constant by quartz-crystal control, a necessary characteristic for easy re-aquisition of signal when using narrow-band receivers. Full details of circuit operation are given by Ferrel *et al.* (11).

Packaging for the earlier Mark III transmitters, which used discreetly wired IC (Integrated Circuit) components, is an oil-filled cylinder (1.3-inch diameter, 6.0-inch long) with rubber end caps (Figure 4). The newer Mark IV units, utilizing hybrid thick-film circuit construction, are in air-filled PVC (Polyvinyl Chloride) cylinders (1.0-inch diameter, 4.0-inch long).

Various sensors were developed (11) for incorporation into the transmitter packages (Figure 5). Presently available are sensors to

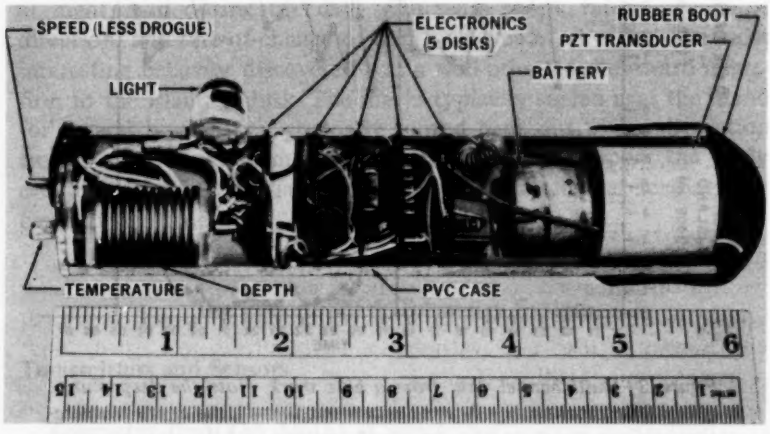

Figure 4–Mark III multichannel transmitter: cut-away view showing internal components of an 8-channel unit with sensors for depth, swim speed, light, and temperature. PZT = Lead-Zirconate-Titanate. PVC = Polyvinyl Chloride.

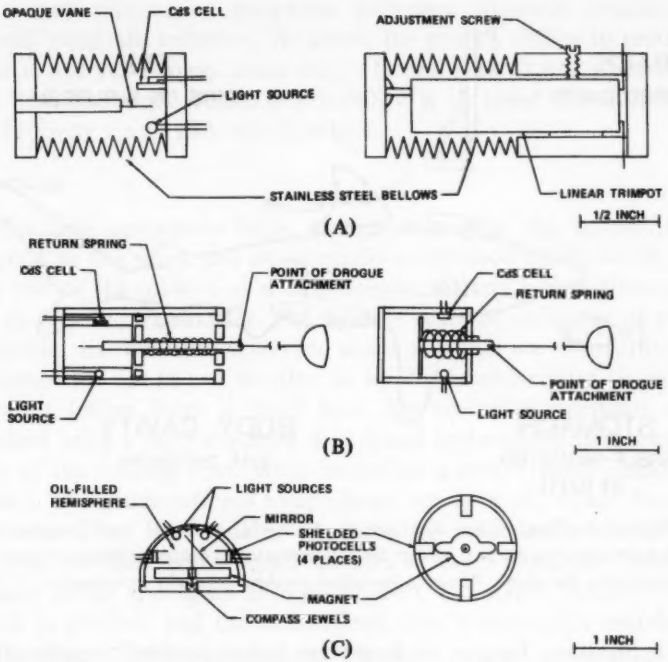

Figure 5—Some representative sensor types utilized in past transmitter packages: A, depth (pressure); B, swim-speed (water flow); C. compass heading (azimuth). All act as variable resistors. The light-photocell types utilize very low-power light-emitting diodes powered by zener-diode regulated voltage from the transmitter battery. Several newer versions are under development which are considerably smaller and without moving parts.

measure depth, swim speed, compass heading, temperature, and light. Under development are additional sensor types to measure stomach acidity, acceleration, and bodily posture.

Total cost per transmitter depends on the configuration adopted, number and type of sensors, and on whether assembly is done by the investigators themselves or by outside contractors. Approximate parts costs for a Mark IV transmitter without a sensor is $60; with a depth sensor, $70 to 100; with depth, temperature, swim-speed, and compass sensors, $100.–150.

Transmitter Attachment—Effects on Behavior

Several methods can be used for fastening the transmitter to a shark (Figure 6). The primary concern is to avoid excessive capture

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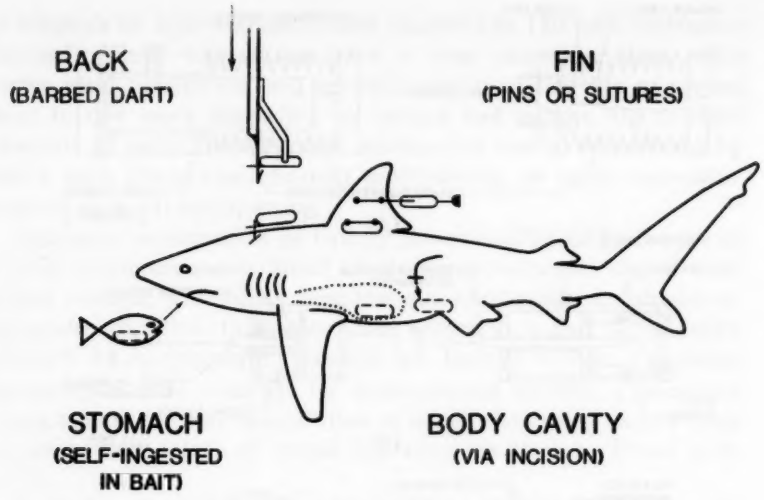

Figure 6—Transmitter application methods, external and internal. Application via barbed dart or by self-ingestion is accomplished without capturing the shark. The self-ingestion method is totally atraumatic.

and application trauma or long-term irritation which might affect data validity. The precise effects are unknown. But it would seem that gross capture and application trauma would considerably affect a shark's behavior immediately after release, and that this effect would diminish with time and eventually disappear. Any irritation caused by the attached transmitter itself, probably persists.

For short-term trackings of hours or days it is thought best to use attachment methods which minimize initial trauma. Two proven methods useable on uncaptured, free-swimming sharks are: (a) external, via a barbed dart thrust in by an applicator pole, and (b) internal, by inducing the shark to swallow the transmitter concealed in bait. The latter method is totally atraumatic and does not appear to affect the shark's behavior at all. The former method usually results in the shark dashing away after being tagged. In the case of externally tagged blue sharks normal behavior appeared to return within 60 to 90 minutes (10). Some individuals seemed almost unaffected, circling back to the bait cannister within seconds after application (Figure 1). On the other hand, some sharks captured and tagged after much vigorous struggling showed probable traumatic effects for many hours after release.

For longer-term studies of weeks or months it may be better to capture the shark and carefully suture the transmitter to its skin or fin

in a way minimizing long-term irritation. Stomach implantation would eliminate irritation. However, the shark's ability to retain the unit is not yet known, some sharks having regurgitated units within the first few days. Another possibility is to insert the unit in the body cavity via an abdominal incision.

Tracking

Tracking operations begin immediately after the transmitter is applied to the shark and are normally maintained continuously until the end of the mission at which time an attempt is sometimes made to recover the transmitter. The signal is detected using one of several tuneable, narrow-band receivers, some of which are waterproof and designed for use in wet weather or by divers underwater (Figure 7). When tracking from a small boat, the operator maintains signal contact using a staff-mounted directional hydrophone held over the side of the drifting boat. When reception is good (strong signal, low noise), an omnidirectional hydrophone can be used, which frees the operator from the tedium of manually maintaining the proper hydrophone aim. When signal strength becomes marginal, the boat is moved closer and again allowed to drift. Estimated location of the shark is plotted, and the telemetered data is stopwatch decoded or tape recorded for later computer reduction.

During good weather and good signal reception, tracking operations are relatively simple and straightforward. In bad weather, with poor signal propagation and high ambient noise, tracking can become difficult, and success depends to a large extent on the skill and determination of the tracker. In certain coral-reef areas with strong currents, rugged bottom topography, and high ambient noise, it may be difficult to maintain unbroken contact with an actively moving shark, and tracking may require that considerable time be spent in searching for and relocating the shark.

Experience has shown that the primary factor limiting the length of a continuous tracking operation is fatigue of the tracking personnel. In studies of blue sharks at sea off California, 24 hours has proven about the limit for continuous tracking by a crew of one or two persons (10). At Rangiroa, French Polynesia, gray reef sharks were tracked continuously for periods up to 96 hours by a crew of four persons, each putting in one solo six-hour shift per day (12).

Transmitter Recovery

If desired, the transmitter package can include a timing mechanism which releases the unit from the shark at the expected end of the

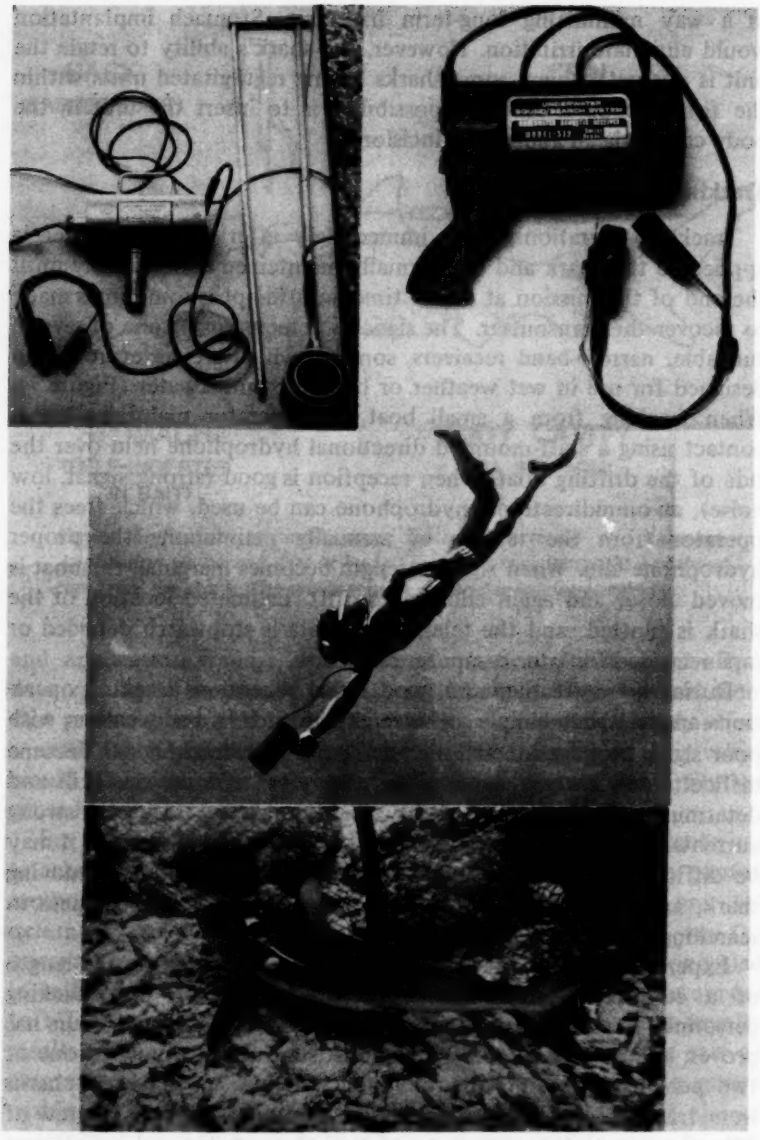

Figure 7—Ultrasonic telemetry receivers, DuKane (top left), and Burnett (top right). Center: free diver using Burnett unit underwater. Bottom: gray reef shark with externally attached Mark III transmitter (in fish trap prior to release for tracking). (Photos by R. McKenzie, top; D. Mosher, center; and R. Johnson.)

tracking. Recovery is then accomplished by a receiver-equipped diver or from the boat if the package is buoyant. Magnesium breakaway links, having predictible corrosion rates, were successfully used for recovery of transmitters from angel and blue sharks (9,10), but release times varied considerably due to differences in water temperature and flow rate. This uncertainty of timing can be discouraging to weary tracking personnel. A precise timing mechanism, based on crystal-controlled digital counting circuitry, is presently being developed.

The decision of whether or not to plan for transmitter recovery is based on the trade-off between the advantages and disadvantages of recovery. Advantages include savings in cost and time, because additional trackings are possible with reuse of the units; and one has the opportunity to inspect units that have been actually used. Disadvantages include the necessity to use release attachments, requiring a larger package having more drag, especially if floatation is needed. In general, validity of data is the most important consideration, particularly for long-term trackings involving many days of boat and personnel time. If there is reason to suspect that a recovery-compatible attachment (e.g., external with float) would substantially affect the animal's behavior, then it would normally not be used. If, however, cost considerations severely limit the number of units available, then the benefits of repeated use of recovered transmitters might outweigh the disadvantages.

Data Recording, Reduction, and Analysis

The simplest way to decode telemetered sensor data is by manual "stopwatch" timing, e.g., pulse rate. This is easily done in the boat, and often suffices for trackings when using one-channel transmitters. Multichannel data can also be field-decoded in this manner if it is in the slow-multiplexed format. Manual timing, however, is adequate only for parameters which are changing relatively slowly, and cannot be used to measure quick-changing events.

The full potential of the multichannel system is realized only with the rapid-multiplexed format, continuous tape-recording of data, and subsequent computer reduction and analysis. The system was designed to detect brief, infrequent behavioral events as well as longer term changes. With all eight transmitter channels sampled in about two seconds (one second if four channels are used), it is unlikely that even brief events, such as sudden accelerations, would be missed.

Data from the receiver output is first conditioned by pulse amplitude and length discriminating circuitry for initial noise rejection. The resulting uniform pulses are recorded, along with coded time-of-day information, at slow tape speed on an analog recorder. Back at the University, the tapes are played at 32 X real time into a PDP-12 computer programmed to digitize the pulse-interval values in milliseconds. The digital data tape thus produced is then processed by the larger CDC-3150 computer programmed for further noise reduction, de-multiplexing, data averaging (when desired), and print-out as eight parallel graphs representing sensor state vs time of day.

Behavioral conclusions are then drawn by visual inspection of the computer print-outs. The averaged graphs would be scanned first. These would include means and ranges for each averaging period. General trends over the day-night cycle would be immediately apparent, and other points of interest would show up (as range excursions) and could be examined in greater detail on print-outs at shorter averaging times, or in full detail with no averaging.

In conjunction with a digital plotter, the computer can be programmed to draw maps showing detailed locomotor patterns of the telemetered sharks. Using combined data from swim-speed and compass-heading sensors, such "micro-path" plots can potentially yield a great amount of behavioral information. As a hypothetical example, a hunting shark might locate prey, circle it closely, then speed in to attack. Such a brief, small-scale pattern would be impossible to detect from the boat by hydrophone direction, but would be readily apparent on the computer map.

Future Telemetry Capabilities

Acoustic Command Functions

Presently under development is a command control system for the existing transmitters. In its simplest form, as a transponder, the unit on the shark would remain silent (*listening* mode) until it received a recognizable signal from the larger command transmitter at the boat. In reply to the command signal, the shark unit would switch to the *transmit* mode for a preset length of time, then return to the listening mode.

The battery-saving effect of transponding is well known; listening circuitry alone draws very little power. For long-term studies where only intermittent checks on the telemetered shark are planned,

useful transmitter lives of up to several months can be accomplished. Another advantage of transponding is that it permits accurate measurement of shark-to-boat distance, thus facilitating more accurate plotting of the shark's position. Receiving equipment at the boat would automatically calculate this distance as a function of transponder reply time.

Besides ordinary transponding, other command functions under consideration are: 1. shift of multiplexing mode (rapid to slow), 2. interrogation of memory bank (see next section), 3. delivery of stimulus to the shark (for experimental purposes), and 4. release of transmitter (from external attachment). Recovery of stomach-implanted transmitters might also be possible by a command-regurgitate mechanism which releases an emetic. If several different command functions are included in one transmitter, the interrogate signal would be coded for proper recognition.

Memory Transmitters

Personnel who have participated in actual tracking studies, especially under adverse conditions in small boats, agree that human fatigue is the primary factor limiting long-term acquisition of telemetered data. When maximum detail is sought on a shark's movements or other type of behavior, then there is no reasonable alternative to continuous tracking. In other studies, however, "continuous" data, but less detail may be desired.

A transmitter with a built-in memory unit would be extremely useful in many such studies. If, for instance, one is interested in a shark's general day-night activity pattern, it would suffice to know its mean swimming speed for each of the 24 hours. Even more could be learned if an upper and lower range value accompanied each hourly mean. A digital storage module capable of accumulating this much data (appx. 500 binary bits) is presently being designed for the shark transmitters. Upon receipt of the proper command code from the boat, the shark unit would send back its stored data, in binary code, in about two minutes. Thus the shark unit need be interrogated only *once each day*, alleviating the tracking fatigue problem, and freeing the investigators for other work.

Memory transmitters could also be programmed for storing locational data on the shark's general daily movements. Special bottom-mounted transmitters placed at strategic sites within the shark's suspected home range could each emit a different acoustic code. The shark unit, when sufficiently near a code transmitter, would recognize and store this information, thus providing data on

the time of day the shark was located in the vicinity of each code transmitter.

An alternative possibility for automatic acquisition of locational data is an array of bottom-mounted receiver/recorder units. If three or more synchronized units are employed, it becomes possible to obtain relatively exact locational data (by comparison of pulse-arrival times), as was done by Hawkins *et al* (13) with ultrasonically-tagged cod in a Scottish sea loch. Such a system, however, is practical only in certain confined environments with good acoustics, which would limit its usefulness when working with sharks.

Submersibles for Tracking and Observation

Small, manned submersibles are potentially of great value for intercepting and observing transmitter-equipped sharks at depths too great for scuba divers. Although many existing dry submersibles have more-than-adequate capabilities for depth, mobility, and life support, these craft are too obtrusive, heavy, and operationally costly to be practical for the above purpose, especially in remote areas. What is needed is a simple, inexpensive, ultra-portable vehicle from which unobtrusive observations could be made at moderate depths.

Currently under consideration for this purpose is a one-man, spherical, acrylic design permitting 360-degree visibility. The feasibility of acrylic spheres for submersible hulls has been thoroughly researched at the Naval Undersea Center and the Naval Civil Engineering Laboratory (14). Tests indicate that a man-size capsule capable of operating safely (safety factor of 4 for short term implosion) to 400-foot depths can be made from one-inch-thick acrylic hemispheres of 40-inch diameter. The proposed craft, consisting mainly of two such hemispheres each weighing 100 lbs in air, would be light enough to be handled by two persons in a small boat.

The capsule would be water-filled, but kept at surface pressure allowing the use of a simple, silent, oxygen rebreather. Water filling would make additional ballast unnecessary, make the craft less visible underwater, and permit the operator inside normal hand-held use of the underwater telemetry receiver. Propulsion would be by two small electric-powered thrusters, or possibly by manual power. The vehicle would also provide protection against shark attack.

Behavioral Information Obtainable by Telemetry

A complex telemetry system is justifiable to a biological research program only if it can yield the desired biological information better

than by other methods. Telemetry is particularly applicable to gathering certain kinds of behavioral information. In the case of sharks, much of this type of data would be difficult or impossible to obtain otherwise.

Day-Night Activity Patterns

The most basic information one gets from telemetry is the animal's location throughout the tracking, from which its home range, and day-night movements, can be plotted. This is the original purpose for which ultrasonic fish tracking was intended, and can be accomplished with the simplest transmitters, "pingers" without sensors, which yield approximate location as a function of signal strength and direction.

Simultaneous tracking of several recognizable individuals can be accomplished if the "pingers" are each set at a different frequency and/or pulse rate, and these must be stable re: temperature, pressure, and battery voltage. Constant frequency is particularly important because drifting frequency can lead to confusion in distinguishing individual units. Tracking personnel must know precisely where to set the tuning dial of the receiver for each individual, especially when searching for potentially marginal signals.

Depth can be determined in addition to location if the transmitter is equipped with a pressure sensor. Individual recognition, in this case, would have to be based on frequency only. Depth is a very useful parameter to monitor, as sharks often show distinct daily rhythms of depth preference or of rate-of-change of depth. Data from a single-channel, swim-speed transmitter can establish a shark's basic day-night activity pattern (diurnal, crepuscular, nocturnal), and whether it ever stops swimming to rest on the bottom. The most complete picture of general activity, of course, comes from multi-channel transmitters having several different sensors.

A shark's basic day-night routine is information directly useable in formulating advice to swimmer/diver personnel. If, for instance, night-diving operations are planned for a given area, it would be valuable to know in advance if dangerous sharks in their active phase are likely to be present. An example of information of this type was reported by Sciarrotta (10), whose telemetered blue sharks unexpectedly moved in close to the Santa Catalina Island shoreline at night.

Feeding Behavior

Very little is presently known about how most large, active sharks, including those dangerous to man, normally obtain their food. While

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some data exist on *what* they eat, from gut contents and preferred baits, surprisingly little is known about *when* they feed, *how often* they feed, and exactly *how they capture* their normal prey. Telemetering technqiues can be used to provide this kind of information.

One method would involve stomach-implanted transmitters which directly detect the intake of food by sensing the changes in pH which occur when food and accompanying water is swallowed, or when stomach secretions increase. Another way would be by recognition of specific behavioral events such as turns, accelerations, or jaw movements, which might be correlated to feeding actions. Multichannel telemetry increases the probability of identifying significant specific events because it allows close time comparisons between two or more factors. For example, sudden direction change (compass sensor) occurring during the same brief time period as sudden speed increase (speed sensor) might turn out to be an event representing a shark chasing a certain type of prey. A different event might consist of tight circling, slow speed at a different depth, and this might indicate feeding on some other prey organism. Such events, even though they may occur only briefly and infrequently, would be readily apparent on the computer print-outs.

It is obvious that detailed knowledge of normal feeding routines is directly applicable to the shark attack problem, especially for very large species such as the tiger shark and white shark. It must be remembered, however, that not all shark attacks on humans appear feeding motivated; and of those that are, some should be regarded as rather opportunistic, non-routine feeding attempts by the shark.

Courtship and Mating

While little is known about natural feeding behavior in sharks, even less is known about social behavioral patterns such as courtship and mating. Courtship in sharks has never been described, and even copulation itself has been illustrated in the literature only from aquarium observations on two small, bottom-dwelling species. For the large, active species, nothing is known of mating, except what can be indirectly inferred from mating scars (tooth marks) on females, or sperm in the claspers (intromittent organs) of males. Questions as to where, when, and how often mating occurs in the natural environment remain completely unanswered. It is intriguing to consider the possibility of approaching these questions with telemetry.

One way would be to search for some specific event believed associated with mating, such as flexing of the claspers. At the beginning of the suspected season of mating, mature males would be captured and fitted with long-term memory transmitters with sensors to detect clasper flexion. Data storage as opposed to continuous tracking would be the most practical initial technique, since the researchers would have very little idea of when or how often to expect the clasper events. The various units could be relocated and interrogated at intervals, perhaps daily or weekly. When indications of clasper activity are found, shorter-term memory would be utilized to determine more accurately the time and place of behavioral responses. It would then be feasible to begin continuous tracking and data recording to obtain the most detailed telemetry picture of such behavior. If conditions warrant, attempts at direct observation of specific behavioral patterns might then be made by receiver-equipped personnel using scuba or submersibles.

Facilitating Observation and Experimentation

Although designed primarily as a tool which itself gathers the desired data, telemetry can also be used to indicate the whereabouts of individual, transmitter-equipped sharks so that other kinds of observations or experiments can be performed on them. For example, observations of the cave-dwelling habits of reef whitetip sharks at Rangiroa, French Polynesia, were aided by marking individuals with stomach-implanted transmitters that operated at identifiable frequencies (15). Divers using underwater receivers could pin-point a shark's location in a particular cave, so that its relation to other sharks in that cave could be studied.

Some accounts suggest that certain sharks may defend geographical territories (16). If this is true, it bears directly on the shark attack problem, especially for those types of attacks now being attributed to agonistic motivations (2,3). In at least one dangerous species, the gray reef shark, agonistic motivations are often manifested during diver-shark encounters as distinct threat displays (3,16). What is needed to confirm territoriality is proof that a given individual shark behaves more aggressively towards intruders in one part of its home range than in other parts. Marking a shark ultrasonically would not only permit delineation of the shark's home range, but would facilitate experimental diver-shark confrontations at various places within the home range.

Field experiments to determine sensory capacities and orientation mechanisms can also be facilitated by telemetering techniques.

Detailed "pictures" of a shark's swimming pattern when detecting and orienting to a test stimulus can help elucidate the mechanism involved, such as whether true directional response or gradient seeking. If desired, a transmitter could command-deliver a stimulus to the shark. For instance, this might be done to distort the earth's magnetic field about a shark's head to determine if magnetic cues are utilized by sharks for navigation at sea, an intriguing possibility that has been raised by recent findings of Kalmijn (17).

The Ideal Shark-Telemetry Transmitter

No one transmitter configuration is ideal for all of the research possibilities. The greatest overall capability would be in a multichannel, transponding, memory-type transmitter having several sensors and additional command functions; but such a unit would be unnecessarily large, complex, and costly for many uses. Smaller single-channel units may be preferred when primarily locational information is sought, and simplicity of data recording is desired. For a given purpose available funds may be most effectively spent on many trackings using simple, inexpensive transmitters, while another purpose may be best served by fewer trackings with units of greater data-gathering capacity.

At the present state of hardware development, the envisioned biological uses often call for new or modified transmitter designs. For instance, if telemetry is planned from very large sharks, it might be best to employ a larger transmitter allowing greater range, added life, and more sensor capacity. In the past, specialized transmitters were usually built by the researchers themselves, often to be tried out for the first time during the actual study. It is anticipated that this situation will improve in the future. One long-range goal of the Navy-supported program at California State University is the development of a whole family of modular transmitter components which can be combined by the investigator into the transmitter configurations best suited for his desired study.

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Unique Optically Pumped Collision Laser

Scientists at the Naval Research Laboratory (NRL) have designed and successfully tested a continuous wave (cw) laser on the 546.1 nanometer (nm) line of Mercury (Hg I) by optically pumping a mixture of nitrogen (N_2) and Hg vapor.

(Continued on Page 45)

Charge-Coupled Device Applications

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and
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Naval Electronics Systems Command

Introduction

Charge coupling is a significant concept because it provides improved performance in terms of dynamic range, sensitivity, noise, power and weight compared to other semiconductor device technologies with less complexity. Also, because of the versatility of the charge-coupled concept, one base technology is applicable to imaging (including low-light-level), analog and digital signal processing, and digital memory. [1].

The basic building block of a CCD is a metal-insulator-silicon (MIS) capacitor. A CCD is simply a closely spaced set of these basic cells.

The operation of a charge coupled device can be understood by using the hydraulic analogy; i.e., water is the analog of electric charge and a bucket is the analog of a potential well. While the depths of the buckets can be controlled by mechanical means, the depth of potential wells in a CCD are controlled by the voltage applied to the electrodes. If light is absorbed in the semiconductor, then electrons are generated and are collected in the potential wells. The analog is rain being collected in the buckets: the amount of rain (electrons) collected in each bucket (potential well) is proportional to the intensity of the rain (light) at that point. In a similar way, the charge configuration in the potential wells is proportional to the optical image focused onto the CCD. The charge configuration representing an image can be shifted out of the device into external electronic circuits by manipulating the potential well depths so that the charge spills to the output end in a serial fashion.

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The important attributes of this device concept are: (1) Since the device is a set of MIS cells on a single slice of silicon, it is basically simple to fabricate using existing metal oxide semi-conductor (MOS) technology. (2) The potential wells can hold a large amount of charge thus allowing the device to be used at high signal levels. The noise generated in the CCD is so small that the device can be used for very low signal levels. The combination of these two factors means that the device has a large linear dynamic range (10,000:1). (3) Charge coupling can be achieved in two dimensions, therefore, two dimensional (area) arrays can be fabricated. (4) The device is operated at low voltages and the power consumption is small. (5) The size of a CCD having TV resolution would be approximately 1/2 × 1/2 inch, so that the size and weight of the device are negligible relative to the lens required for imaging. (6) Because the device can potentially be mass produced on a production line, by standard semiconductor fabrication techniques, the projected cost is low. (7) Because the device is completely solid state, is simple, and has no inherent burn-out mechanisms, the reliability is expected to be excellent.

The combination of small size, low weight, low cost, low power consumption, and low-light-level capability provides new military imaging capabilities such as guidance for small bombs, artillery shells, and missiles where the size, weight and power requirements of other imaging sensors are too large. The same considerations indicate a vastly improved capability for navigation and guidance, surveillance, reconnaissance, target recognition, mapping, change detection, pollution detection and monitoring, earth resource detection, starfield mapping, character recognition, and page reading. The improved capability is primarily due to the fact that the low cost and long life allow them to be used in mass quantities in military systems.

Basically, a one dimensional CCD is an analog shift register; i.e., time sampled analog information is shifted in discrete time steps. The CCD delay line is a small chip (0.1 × 0.2 inches) whose electrical length can be controlled electronically. The use of CCD's in this mode will be of great value in applications such as radar and sonar, where a small signal must be extracted from a noisy signal. Presently analog signals are processed by performing an analog-to-digital conversion with subsequent signal processing by digital techniques. While this method works well, the power, weight, size and cost requirements are large. The potential use of CCD's to process analog data by truly analog techniques indicates that complicated signal processing functions (delay, correlation, multiplexing) can be achieved with CCD's with savings of power, weight, volume, and cost

each by approximately a factor of 2-10 as compared with conventional means.

One or two dimensional CCD arrays can also be used in a binary mode (potential well either full or empty) to process and store digital information. Because of the high-density, low cost potential (0.1¢/bit as compared with 1-10¢ bit with other solid state technologies) of CCD memory, this approach would provide a new capability for mass storage in military applications.

Operation

The operation of a charge coupled device (CCD) can be analyzed in four parts: storage, transfer, input, and output. Each of these will be discussed separately.

Storage

The basic element of a CCD is the MIS capacitor. The important properties of an MIS capacitor as it applies to CCD's can be explained in terms of Fig. 1 which shows an MIS capacitor utilizing a P-type semiconductor. [2] When a positive voltage is applied to the metal at t=0, majority carriers are repelled and leave the semiconductor in a few relaxation time constants thereby forming a region near the semiconductor-insulator interface depleted of majority carriers. The energy diagram representing the situation is shown in Figure 1A, and it is convenient to think of this as an empty potential well of depth ϕs_o. There is, of course, an electric field to attract minority carriers toward the semiconductor-insulator interface. In the absence of external excitation, the only source of minority carriers is thermal generation. In well prepared, indirect gap semiconductors this is a slow process, and the time required for equilibrium to be reached can be many seconds. This storage time, t_s, is 4-6 orders of magnitude greater than the minority carrier lifetime, τ; i.e., $t_s = 2\tau\ N_A/n_i$, where N_A is the substrate doping and n_i is the intrinsic carrier density. If minority carriers are generated in the depletion region (or within a diffusion length of it) in response to a signal, then this minority-carrier charge, representing information, will accumulate in the potential well and partially fill it as shown in Figure 1B.

Thus, the potential well (depletion region) formed by applying a positive voltage to the metal electrode of an MIS capacitor is used to collect and store charge. The thermal generation of hole-electron pairs and subsequent collection of the minority carrier constitutes a leakage current (termed dark current in imaging). Typical dark current densities are 10-100 nA/cm^2.

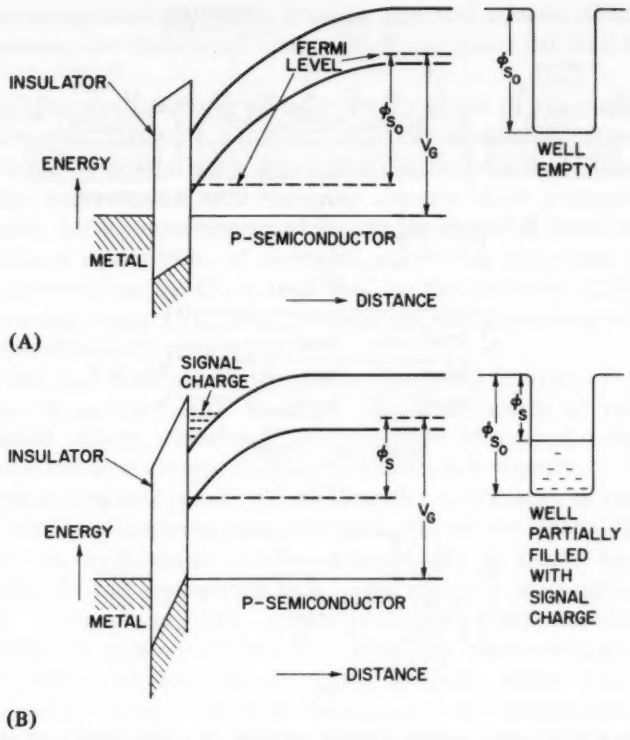


Figure 1–Energy level diagram of MIS capacitor. A. Empty potential well. B. Partially filled well

Transfer

A CCD is simply a coupled set of MIS capacitors as shown in Figure 2. The signal charge stored in potential wells at the Si-SiO_2 interface is localized under the metal electrodes and is therefore in the form of charge packets.

The way in which the charge packets (information) are transferred toward the output is shown in Figure 2, which shows a primitive charge coupled device.

Three phase clocking is used as shown in the timing diagram (D). Suppose that at $t = t_1$, $\phi_1(t_1) = V$, $\phi_2(t_1) = \phi_3(t_1) = 0$, then deep potential wells exist under phase 1 electrodes as shown in (B); further, suppose some signal charge is in these wells as shown in (C). At t_2, phase 2 electrodes also go to +V, and deep potential wells are formed underneath allowing some of the charge to diffuse from the

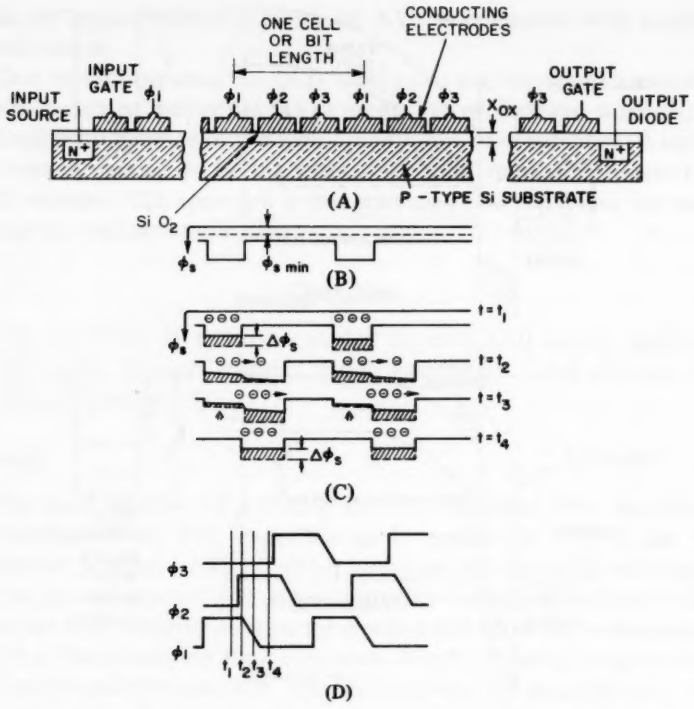


Figure 2–Charge coupled transfer process. A. Cross-section of the charge coupled structure. B. Surface potential profile at the beginning of the transfer cycle. C. Surface potential profiles during the transfer cycle. D. Three-phase clock waveforms

ϕ_1 wells to the ϕ_2 wells. At t_3, the ϕ_1 wells are reduced in depth while the ϕ_2 wells are increased in depth thereby creating an electric field which forces the charge into the ϕ_2 wells. The process continues, and the charge is moved one cell or bit length every period of the clock. For the CCD described above using a planar oxide and uniformly doped semiconductor, three clocking phases are required to give a surface potential profile which allows charge to be transferred toward the output while preventing charge from flowing backwards toward the input. Three-phase clocking is somewhat inconvenient because it requires either two-level metallization or a diffused clock line for the third phase. The surface-potential profile required for unidirectional transfer can be achieved for two phase operation by the use of a stepped oxide or nonuniform substrate doping. [3, 4]

Two interrelated quantities, transfer time and transfer efficiency, characterize the transfer of charge from one potential well to the next.

The dynamics of charge transfer are governed by the continuity equation and Poisson's equation with the appropriate boundary conditions. In general both drift and diffusion contribute to charge transfer; however, in well designed devices, drift processes are dominant. Drift current is caused by (1) the electrical field due to a nonuniform distribution of electrons under two electrodes at the same potential or by (2) a field due to the potential difference between electrodes. [5] These processes are called self-induced drift and fringe-field drift respectively.

Self-induced drift usually dominates the initial transfer of charge, whereas fringe-field drift dominates the latter stages of transfer. Incomplete charge transfer ($\epsilon > 0$) occurs because the transfer process is too slow compared with the operating frequency.

Another mechanism which limits transfer inefficiency is trapping at the semiconductor-insulator interface. The silicon-silicon dioxide interface is a transition region, perhaps 20 Å thick, between crystalline Si and amorphous SiO_2. This region is characterized by variable composition, SiO_x ($0 \leqslant x \leqslant 2$), and positional disorder becoming less ordered towards the oxide. The electronic properties of this region produce the so called interface states. The total interface-state density, deduced from quasi-static measurements (all states responding), has a minimum near the center of the silicon bandgap and is montonic increasing near the band edges. At higher frequencies, only states having small time constants (nearest the silicon) can respond in which case the interface-state density is smaller and has maxima near the band edges. The principal effects of interface states are: (1) to capture and release carriers during the storage and transfer thereby contributing to transfer inefficiency and noise, and (2) to function as generation centers thereby contributing to transfer inefficiency and noise, and (3) to function as generation centers thereby contributing to the leakage or dark current. The particular states which contribute to charge transfer inefficiency depend on the clock frequency f_c. States near the conduction-band edge emit trapped electrons quickly after the charge transfer process is initiated and these electrons rejoin the main packet; therefore, traps with emission times $<< 1/f_c$ do not contribute to charge transfer inefficiency. States having emission times $>> 1/f_c$ result in an almost permanent trapping and therefore do not contribute to charge-transfer inefficiency on a steady-state basis. Therefore, it is states having emission times $\approx 1/f_c$ which trap charge from a packet

and emit charge into trailing packets, thus contributing to charge-transfer inefficiency. There are two approaches for circumventing the effects of interface states; they are the bias-charge approach (also called the Fat Zero approach) and the buried channel approach. In the bias-charge approach, some charge is maintained in the wells in an attempt to keep the interface states filled thus preventing them from trapping signal charges. [6] The object of the buried channel approach is to prevent the carriers from contacting the interface. This consists of using a shallow ion-implanted or epitaxial layer under the insulator having doping opposite to that of the substrate as shown in Figure 3. The implanted layer is depleted by reverse biasing the implanted layer-substrate junction. [7] Figure 3 shows the resulting potential profile. As a result of the implanted layer, the potential minimum is in the silicon rather than at the interface. Since the signal charge accumulates at the point of minimum potential, the storage and transfer of carrier occurs in the silicon rather than at the

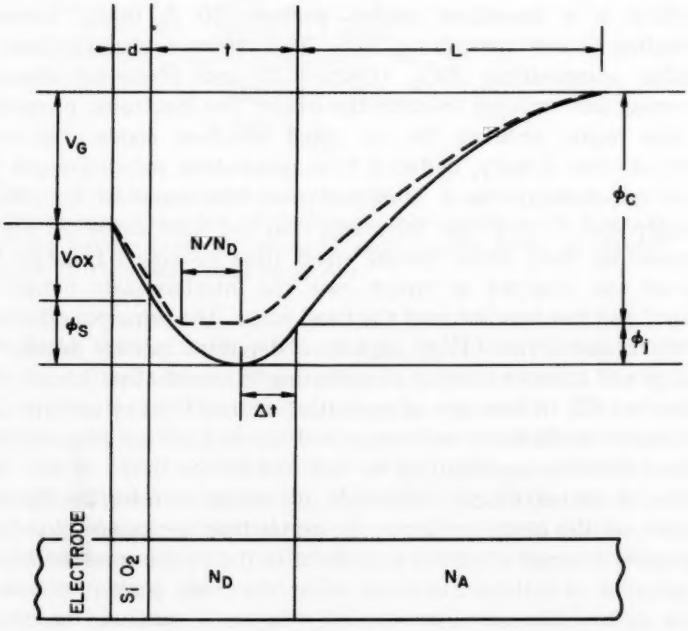


Figure 3–Potential vs. distance into the silicon for a buried-channel MOS capacitor. The solid curve shows the potential with no signal charge present (N = o). The dashed curve shows the potential with N carriers per unit area in the potential well.

interface thereby minimizing the effects of interface states. Transfer efficiencies of 99.999% have been achieved using this "buried channel" technique. [7] The buried-channel device is also better for high frequency operation because of larger fringe fields. Buried channel devices having 5 micron thick epitaxial N regions have been operated up to 135 MHz.

Figure 4 shows an example of transfer inefficiency measurement for a shift register. The shift register is clocked to provide an integration period with a subsequent readout via shift-register transfer. Charge is entered into a cell by means of a small light spot. The oscilloscope trace in Figure 4 shows the output voltage. If the spot is focused on a cell which is m transfers away from the output, the transfer inefficiency is

$$\epsilon = \frac{1}{m} \quad \frac{T}{P},$$

where P is the height of the primary response signal and T is the height of the next trailing pulse from the cell. For the case shown, P = 51 mv, T = 3.5 mv, and m = 257; therefore $\epsilon = 2.6 \times 10^{-4}$.

Input

Two input schemes are shown in Figure 5. Figure 5A shows the method for entering analog and digital information serially. If the

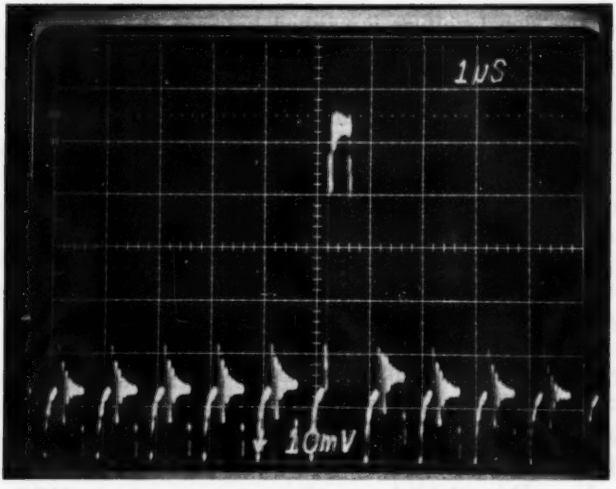


Figure 4—Oscilloscope traces of CCD output.

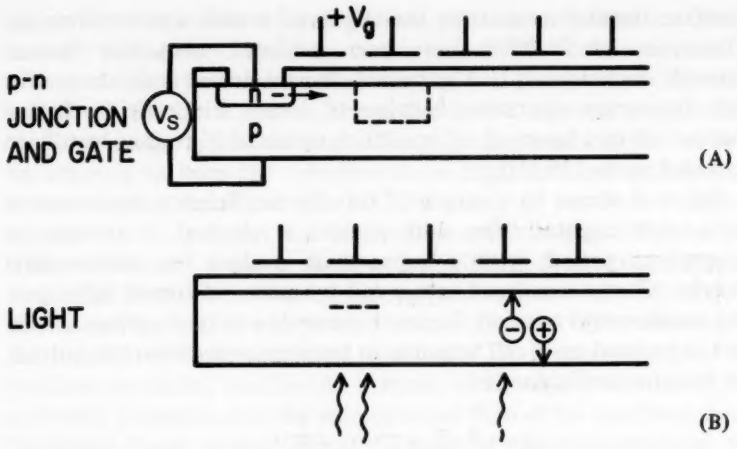


Figure 5–Input schemes for charge-coupled devices. A. Electrical signal input. B. Photon excitation

diffused n-region is connected to the substrate, it will act as a source of minority carriers. If an appropriate bias voltage is applied to the input gate (first electrode) the conduction of minority carriers from the n-region to the first potential well will result; this constitutes a time sampling of the signal voltage applied to the input diffusion. Clearly, charge can also be entered in a digital format by this method.

An analog signal can be entered into the device in the following way: If the signal voltage is applied between the n-region and the substrate and the input gate is maintained in the conducting state, the potential of the n-region and thus the charge entering the first potential well will follow the analog signal.

If an image is projected onto the array of potential wells (from above or below) as shown in (B) minority carriers generated within a diffusion length of the wells will accumulate in the wells in proportion to the photon fluence, thereby creating a charge configuration representing the image.

Output

The signal is read out by clocking the charge packets into a reverse-biased diode as shown in Figure 6. A typical output circuit is also shown in Figure 6. The read out sequence is as follows: (1) the output diode is reverse biased through the reset switch to a reference voltage V_{DR}. This establishes a reference current in the MOS preamp

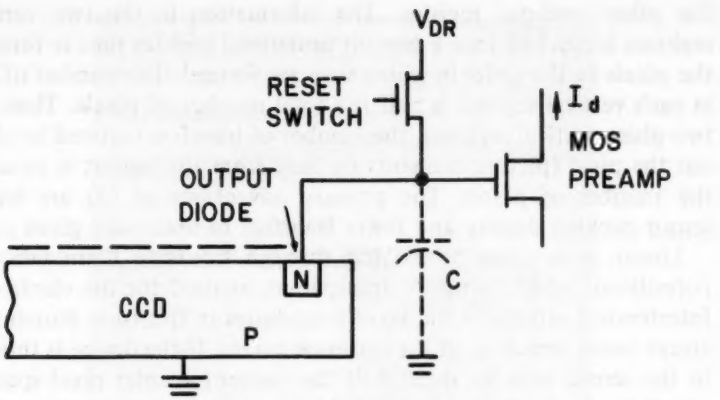


Figure 6–Output circuit for CCD.

($I_{DR} = V_{DR} g_m$). When a charge packet (Q_s) is clocked into the diode, the diode partially discharges, and the MOS preamp current is modulated ($\Delta I_D = g_m Q_s/C$ where I_D is the drain current of the MOS preamp, g_m is the transconductance of the MOS preamp, and C is the capacitance from the output diode diffusion to ground).

Applications

Imaging

One of the obvious uses of CCD's is for self-scanned imagers. The charge coupled approach offers the advantages over other sensors of built-in sensing and scanning.

Linear imaging arrays can be designed three ways. (1) a simple CCD shift register can be used if it is clocked in such a way that the shift-out time is very much less than the integration time. This condition reduces image smear caused by shifting pixels through light sensitive regions. (2) An imager can also be designed with separate sensors and shielded read-out register. After integration in the sensors, the charge configuration is shifted into the shift register; i.e., a parallel-to-series transformation is affected. The line of video is then shifted out via the shift register while a new line is being integrated. This design effectively eliminates the image smear problem. (3) The third design uses a line of sensors and two shielded read-out registers. After integration, odd numbered pixels are shifted into one read-out register and even numbered pixels are shifted into

the other read-out register. The information in the two vertical registers is clocked into a two-bit horizontal register thus re-forming the pixels in the order in which they are formed. The number of bits in each vertical register is half the total number of pixels. Thus, for two-phase vertical registers, the number of transfers required to clock out the pixel (picture element) farthest from the output is equal to the number of pixels. The primary advantages of (3) are higher sensor packing density and fewer transfers to read out a given pixel.

Linear arrays can be excited through frontside illumination if polysilicon, which is nearly transparent, is used for the electrodes. Interference effects at the layer boundaries in frontside illuminated arrays cause structure in the response curves. If the device is thinned in the sensor area to about half the center-to-center pixel spacing, and if the backside is accumulated to minimize recombination at the back surface, the array can be backside illuminated. In this case, losses due to multiple reflections at layer boundaries which occur in frontside illuminated devices are eliminated; also, the structure in the response curve is eliminated.

Table 1 gives the parameters of linear imagers which have been fabricated.

Figure 7 shows an example of imaging from 1728 element, high-resolution buried-channel array to be used in facsimile applications.

In applications where the CCD imaging chip has a velocity relative to the object to be imaged, the CCD can be used in the time delay and integration (TDI) mode to enhance the signal-to-noise ratio. In such applications which lend themselves to this mode of operation, a CCD composed of N_x columns each containing N_y bits is oriented in such a direction and clocked at such a rate that the transfer of pixels

TABLE 1
Linear Imaging Chips

Manufacturer	Number of Resolution Elements	Cell length (mils)	Technology	Design
Bell Labs	1600	0.63	SC	S + SRR
Fairchild	1728	0.53	BC	S + DRR
RCA	500	1.2	SC	SR
TI	500	1.2	SC	SR

SR = shift register
S + SRR = sensors plus single readout register
S + DRR = sensors plus double readout registers

Figure 7–Image of a facsimile chart imaged with a 1728 element buried-channel linear CCD array.

down the CCD columns compensates for the movement of the image along the CCD columns due to the relative velocity of the chip and the object. After N_y bits of time delay and integration, the signal is $N_y S_p$ where S_p is the signal representing a single bit with TDI.

Previous approaches to solid state area arrays used X-Y addressing of sensor elements for read-out. These arrays were plagued by (1) noise in the video passband due to capacitance feedthrough at the X-Y crossover and (2) element-to-element nonuniformities in response and leakage. No. X-Y crossovers are required in CCD area arrays since charge packets can be moved in two dimensions. Also since the storage element in a CCD is simply an MIS capacitor, the uniformity of response and dark current are better.

There are two basic ways of organizing CCD area arrays: frame-transfer and interline-transfer. Figure 8 illustrates the operation of the two schemes. In both cases two-phase structures are shown with 2:1 interlace in the vertical direction. In the frame-transfer structure, the top half of the chip is photosensitive. Field A is formed by collecting photo-electrons under the ϕ-1 electrodes for

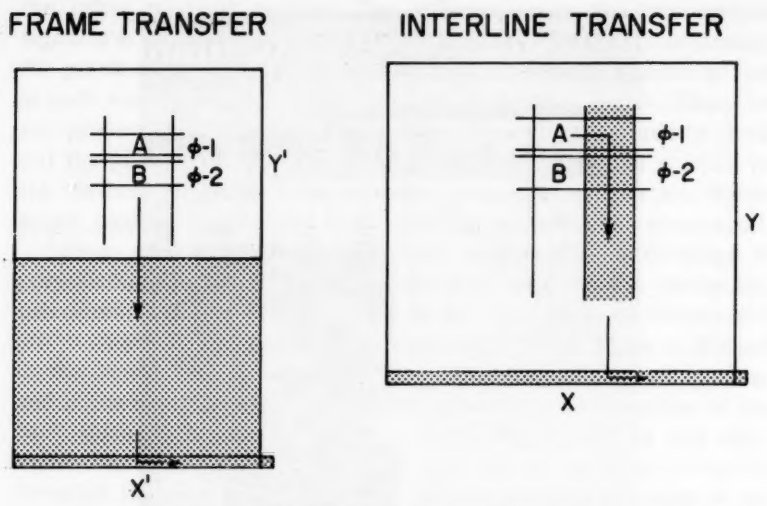


Figure 8–Two-phase CCD area array structures showing the operation of the frame transfer organization and the interline transfer organization.

1/60 second. This charge configuration is shifted into the shielded storage register in typically 1/600 second. Field A is then read-out a line at a time while Field B is being formed by collecting photoelectrons under the ϕ-2 electrodes.

In the interline transfer structure, the shielded vertical read-out registers are interdigitated with the vertical photosensitive registers. Potential wells are formed in the photosensitive regions by applying voltages to the vertical polysilicon stripes. Horizontal polysilicon stripes are used to clock the vertical shielded registers. Because the integrating cells and shift-out cells are separate, the effective integration time for both Field A and Field B is 1/30 second. The operation is as follows: After collecting photoelectrons in Field A for 1/30 second, the charge configuration is shifted into the shielded registers and down, a line at a time, into the horizontal output register. When Field A has been completely read-out (1/60 sec), Field B is shifted into the shielded registers and out.

The use of 2:1 vertical interlace in both structures effectively doubles the vertical sampling frequency, and the resulting Nyquist limit is 1/p where p is the center-to-center spacing (pitch) of adjacent resolution elements in the array. Table 2 gives the design parameters of state-of-the art area arrays.

There are two basic designs for CCD low-light-level imaging chips; backside illuminated frame transfer (BIFT) and frontside illuminated

TABLE 2
Area Imaging Chips

Manufacturer	Number of Resolution Elements*	Image Format $(mils)^2$	Technology	Design	Amplifier
Bell Labs	256 X 220	200 X 260	SC	FT	Reset
Fairchild	244 X 190	170 X 220	BC	IT	DFGA and DDA
GE	244 X 188	340 X 450	SC	CID	OFF CHIP
RCA	512 X 320	310 X 380	SC	FT	Reset
TI	150 X 100	90 X 120	SC	FT	Reset

*Includes 2:1 interlace in the vertical direction
SC = surface channel
BC = buried channel
FT = frame transfer
IT = interline transfer
DFGA = distributed floating gate amplifier
DDA = dual differential amplifier

interline transfer (FIIT). The BIFT design utilizes a thinned chip, while the FIIT design utilizes transparent polysilicon electrodes.

In order to obtain the best possible performance from a CCD array, it is necessary to maximize the signal-to-noise ratio. The noise is basically determined by the technology used (surface channel or buried channel) and by the noise characteristics of the amplifier. On the other hand, the responsivity is largely determined by array design.

The sources of noise in CCD's are [8] noise in the signal (photon noise), fixed-pattern noise due to nonuniformities in dark current from element-to-element, shot noise in the dark current, noise associated with the introduction of Fat Zero, interface-state noise, reset noise, and amplifier noise. The effects of dark current can be virtually eliminated by cooling to - 20 to - 50°C. The minimum noise due to Fat Zero injection is $q_n = (kTC_1)^{1/2}$, where C_1 is the input capacitance, k is Boltzmann's constant, and T is the absolute temperature. This noise source applies only to surface-channel devices since buried-channel devices do not require Fat Zero. Similarly, interface-state noise is applicable only to surface-channel devices, since the buried-channel prevents the signal charge from interacting with interface states. The noise due to resetting the output diffusion is $q_n = (kTC_o)^{1/2}$, where C_o is the capacitance of the output node.

There are basically two approaches to low-noise readout and preamplification: (1) correlated double sampling (CDS) [9], and (2) the distributed floating gate amplifier (DFGA) [10]. In the CDS technique, the voltage at the output diffusion shown in Figure 9 is

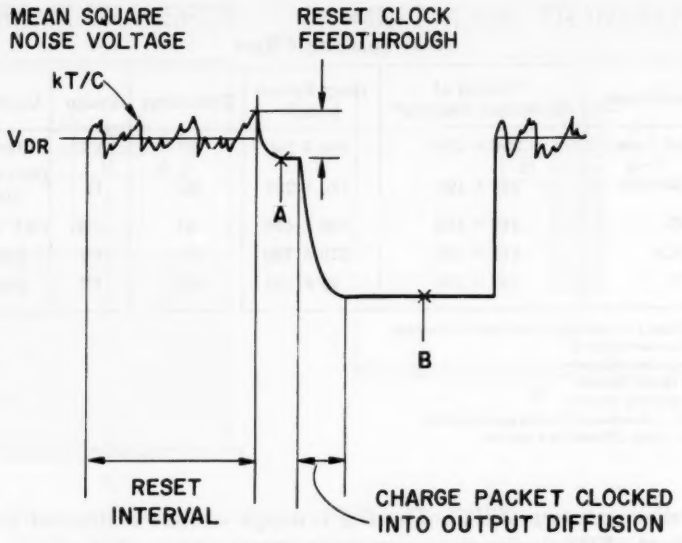


Figure 9–Output voltage waveform of a CCD operated in the reset mode.

sampled after reset (A) and also after the charge packet has been clocked into the diffusion (B). A subtraction of these two samples eliminates the kTC noise associated with the reset of the output diffusion. The remaining noise due to the MOS preamp is 20-50 electrons per pixel per frame.

The DFGA, shown in Figure 10, makes use of floating gates in the SiO_2 over the input CCD channel. Each floating gate controls charge flow through an MOS transistor and into the output CCD as shown in Figure 11. While a charge packet is under a floating gate, charge flows from the source of the MOS transistor into the output CCD resulting in a charge gain of $G_q \sim 20$ at 8 MHz at each state. Since the input and output CCD's are clocked in synchronism, each electron in the input CCD produces G_q electrons in the output CCD at each stage. Since the noise introduced by each amplifier stage adds incoherently while the signal adds coherently, the effect of the noise added by each amplifier stage can be made negligible by using many stages ($M \sim 12$). Noise levels of 10 electrons per charge packet has been achieved with this technique.

Figure 12 shows the results of a simulation of CCD performance [11]. In the simulation, the signal-to-noise ratio of an I-SIT (intensified silicon intensified target) tube was controlled by adjusting the input irradiance and the gain of the intensifiers to

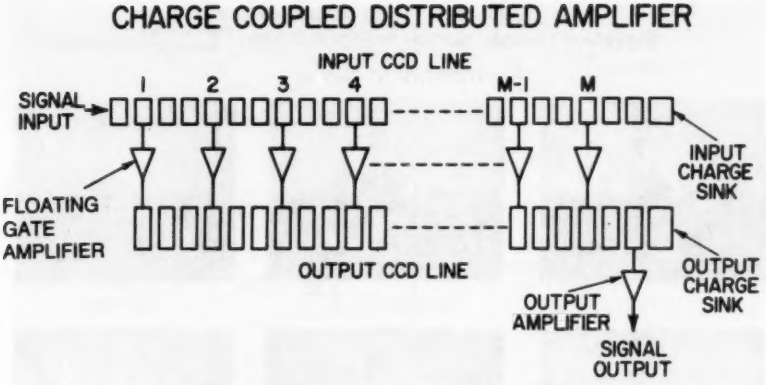


Figure 10–Schematic diagram of the distributed floating gate amplifier.

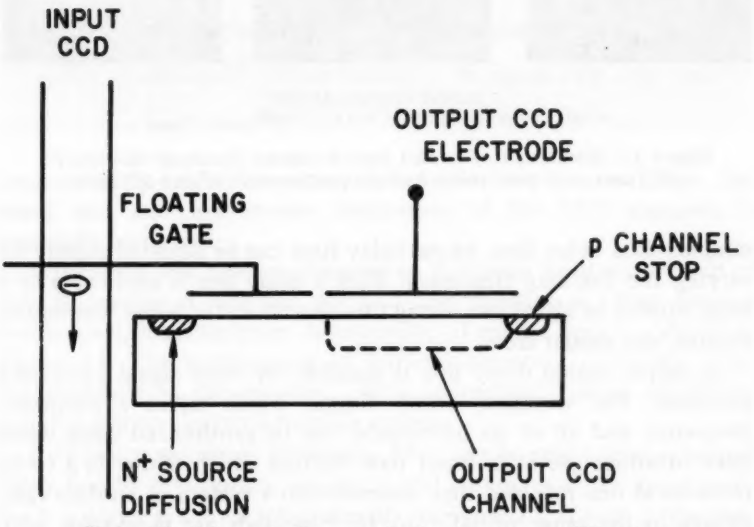


Figure 11–Schematic diagram of a floating-gate amplifier stage.

simulate a CCD having a responsivity of 20 mA/watt [12] and an amplifier noise of 10 electrons. The upper three pictures of Figure 12 show actual I-SIT imagery, and the lower three pictures show the CCD simulation.

Signal Processing

The CCD technology has the potential for making a great impact in signal processing applications. The CCD is inherently an analog,

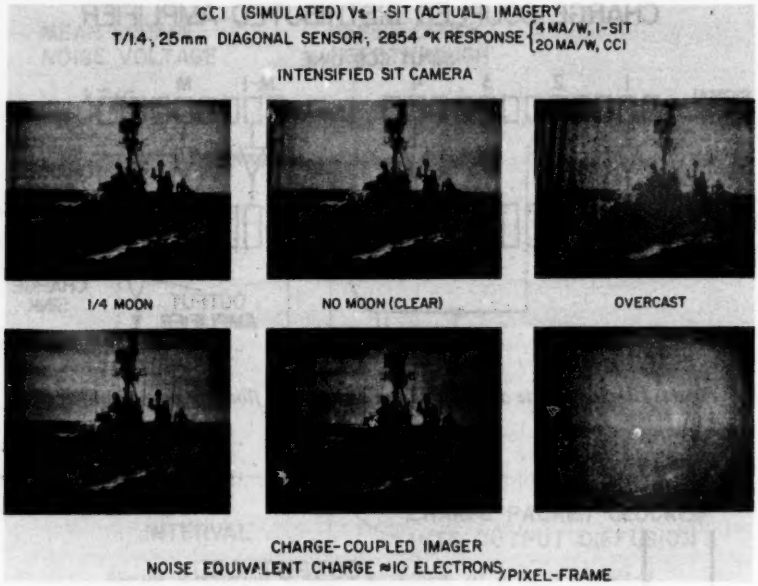

CCI (SIMULATED) Vs. I-SIT (ACTUAL) IMAGERY
T/1.4, 25mm DIAGONAL SENSOR; 2854 °K RESPONSE {4 MA/W, I-SIT / 20 MA/W, CCI
INTENSIFIED SIT CAMERA
1/4 MOON
NO MOON (CLEAR)
OVERCAST
CHARGE-COUPLED IMAGER
NOISE EQUIVALENT CHARGE ≈10 ELECTRONS/PIXEL-FRAME

Figure 12–Simulation of cooled buried-channel frontside illuminated CCD area array performance vs. the performance of an I-SIT tube.

sampled-data delay line, whose delay time can be adjusted merely by varying the clocking frequency. Such a delay line is applicable to a large number of signal processing functions in radar, sonar, communications, and similar areas.

A simple analog delay line is suitable for some signal processing purposes. For example, comb filters, which reject a particular frequency and all of its harmonics, can be synthesized using delay lines. Another use is in input data buffers which allow data to be received at one rate and then entered into a system at another rate. Delays in the range of 10^{-1} to 10^{-6} seconds are reasonable with current CCD technology.

Another processing element is made by providing taps at various points along the length of the delay line. A number of possible applications exist, one of the more important being beam-forming for sonar systems. In such a beam-former, the hydrophones are each connected to a delay line. If each delay line is tapped at multiple points, chosen to cancel the relative propagation delay of the signal at the hydrophone for a chosen beam direction, multiple beams can be formed by appropriate summing of the signals. Figure 13 shows a five-element array with two beam directions, and illustrates how the

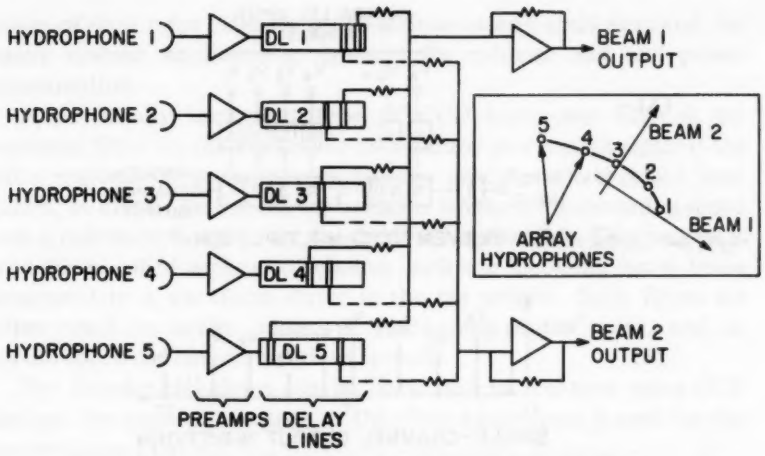


Figure 13–Schematic diagram illustrating the use of CCD delay lines for sonar beam forming.

beam-forming might be accomplished. For use in sonobuoys, the small size and low power dissipation of the CCD elements is especially attractive.

If the delay line taps are designed so that both input and output of data is possible at each tap, the CCD can function as a time-division multiplexer/demultiplexer. A schematic of such a device is shown in Figure 14. The multiplexing of infrared detectors, especially when accomplished in the cryostat, offers appreciable system simplification for scanned infrared imaging systems.

A very general signal processing filter can be made from a tapped delay line by appropriate weighting and summing of the tap signals. Such a device is shown schematically in Figure 15. If such a filter has a portion of the output returned to the input (feedback) it is known as a recursive filter. If feedback is not present, the filter is a non-recursive or transversal filter. Presently, the difficulties of integrating a feedback network having acceptable tolerances have made recursive CCD filters less attractive than the transversal type. A transversal filter can produce most linear functions of an input signal, including low-pass, high-pass, and band-pass filters. If the filter tap weights can be altered by an electrical signal, the filter is capable, in principle, of realizing any linear function of an input signal. The CCD transversal filters potentially offer low noise; wide dynamic range (60-80 db has been achieved); the ability to function over a wide

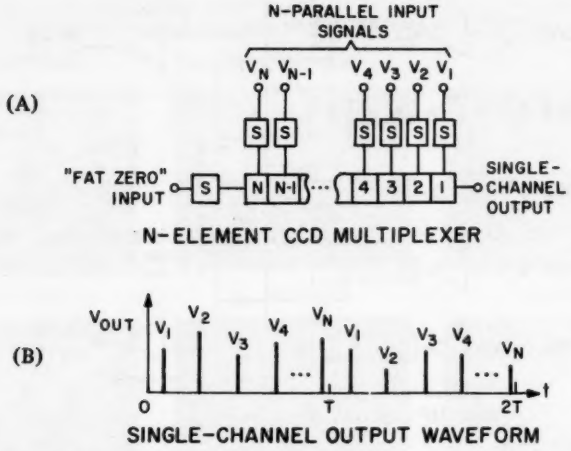
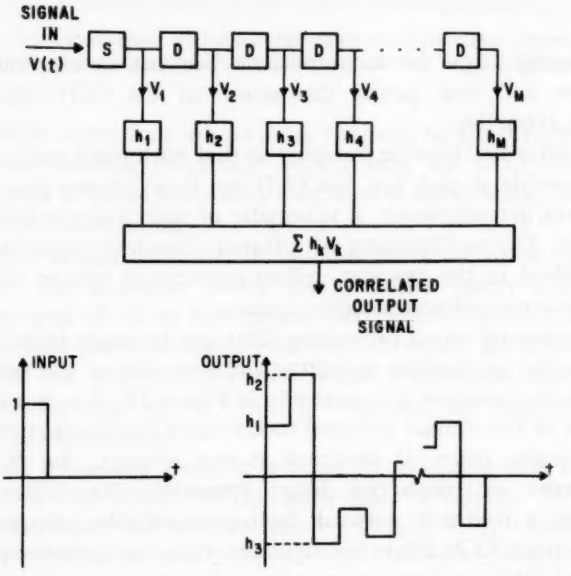


Figure 14—Diagram illustrating the operation of CCD's in time-division multiplexing. A. Multiplexer schematic. B. Multiplexer output.



$$v_{out}(nT_c) = \sum_{k=1}^{M} h_k \, v_{in}(nT_c - kT_c)$$

$$= \int_0^{T_d} h(\tau) \, v_{in}(nT_c - \tau) \, d\tau$$

Figure 15—Block diagram of a CCD transversal filter.

range of data rates (100 Hz to 10 MHz or more); small size; and, for many systems applications, substantially reduced cost and power consumption.

A potentially important type of CCD transversal filter is the matched filter. (A filter is said to be matched to a certain signal if the filter response to an impulse is the time inverse of that signal.) Such filters, in effect, perform a convolution between the incoming signal and a reference function set by the filter tap weights. This process is sometimes called replica correlation, with the incoming signal being compared to a waveform stored in the tap weights. Such filters are often used in active sonar, in pulse-compression radar, and in spread-spectrum communications systems.

The Fourier transform can be computed in real-time using CCD devices. An algorithm known as the chirp z-transform is used for the computation [14].

An interesting possibility is the use of CCD devices for performing correlation between two signals [13]. Such an arrangement could provide adaptive filters for such applications as MODEMS, voice recognition, and adaptive sonar beam-forming.

Charge-coupled devices are also attractive for use in certain digital signal processing systems [15]. The usual logic elements (NOR, NAND, etc.) can be implemented using CCD technology. In addition, shift registers, full-adders, and digital memories can be realized. Using these basic blocks, more complex functions (such as multipliers) can be formed. By combining the proper functions, powerful signal processing blocks can be synthesized. Examples are Fast Fourier Transform blocks and Digital Correlator blocks. Compared to conventional digital circuits, CCD elements offer substantial advantages in terms of bit density and power consumption. Compared to analog circuits, CCD digital circuits have greatly relaxed individual device performance requirements.

Digital Memory

The ability of the CCD to store information suggests its use as a digital memory element. In this application, the CCD is operated as a shift register with data being entered, shifted through the device, and then recirculated. A specific bit can be retrieved as needed by shifting it to a detector.

As a practical matter, the operation of such a memory is limited by the transfer inefficiency and by the thermal generation current. Transfer inefficiency tends to remove charge from leading "1's" and add it to following "0's". Thermal generation adds charge to both the

"1's" and the "0's" with time. These limitations mean that for long registers or low transfer rates, the distinction between a "1" and a "0" becomes lost. This tends to restrict CCD memories to short registers (containing few bits of information). However, this problem can be circumvented by the use of signal restoring or refresh stages along the register. In effect, the register is divided into a number of sub-registers with the signal being restored or refreshed at the end of each sub-register. This would allow an arbitrarily long register to be synthesized by connecting subregisters together. Even with refresh, the CCD cannot be used as a static memory since the thermal generation currents would eventually fill all the wells, converting all of the stored data to "1's."

The CCD memory has potential application in peripheral or auxiliary memories for large computers and in memories for special purpose signal processing computers (such as in radar systems).

For use as a peripheral memory, characteristics of CCD memories place them somewhere between main memory and conventional auxiliary memory. The CCD memory implies a much lower cost than main memories (semiconductor and core) and much higher speeds than conventional auxiliary memories (magnetic disc and drum). Figures 16 and 17 illustrate this point. The CCD memory will fill a

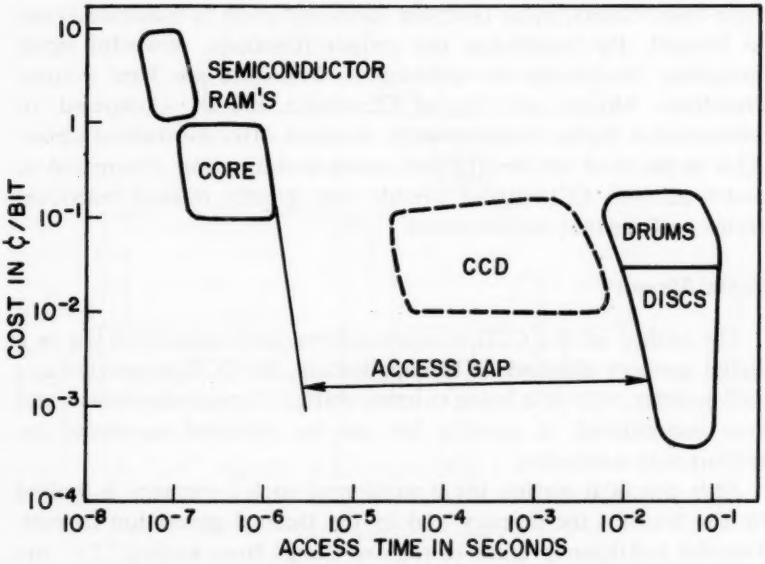


Figure 16–Memory cost (at the systems level) vs. access time.

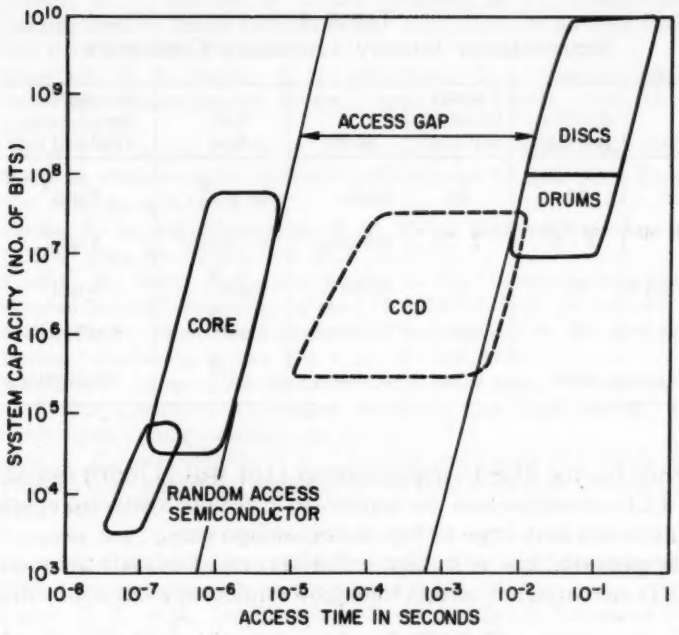


Figure 17–Memory-system capacity vs. access time.

large part of the so called "access gap" between core memories and current mass memory. For some applications, the potential speed, size, and reliability advantages of CCD memory compared to magnetic disc and drum memory will be significant. Magnetic memories do have the advantage of being nonvolatile, whereas with a CCD (and most semiconductor memories) the data are lost when power is removed. Magnetic bubble memories, although small and reliable, still would be substantially slower than CCD memories.

For applications where only moderate access times are required (100 microseconds to 10 milliseconds) CCD memories offer some significant advantages over most other technologies with respect to cell size, number of junctions required, and number of contact openings required. Simpler processing suggests the possibility of higher yields and lower costs, while small cell size would allow very high bit densities. A comparison of some semiconductor memory technologies is given in Table 3.

The use of CCD memories has been considered for some specific systems and some memory elements have been fabricated. Bell Northern Research, for example, has built a 1 megabit memory, using CCD shift registers, which is designed to replace fast disc

TABLE 3
Semiconductor Memory Technology Comparison

Type	Junctions per Cell	Contact Openings per Cell	Mode	Cell Size	Access and Sense Area (200 mil chip)
CMOS	12	12	Static	12 mil^2	6 mil^2
MOS	2 - 8	2 - 8	Dynamic	2 - 6 mil^2	4 mil^2
BIPOLAR	12	18	Static	9 mil^2	6 mil^2
BB	2	None	Dynamic	2 mil^2	Negligible
CCD	None	None	Dynamic	1 mil^2	Negligible

memory for the PDP-11 minicomputer [16] Belt [17] has estimated that CCD memories can be applied to real-time synthetic aperture radar systems with large savings in cost and power.

The potential low cost, high reliability, and moderate access time of CCD memories are certain to suggest numerous other applications.

Conclusions

The charge-coupled device is useful in visible imaging, analog and digital signal processing, and digital memory applications. Linear and area CCD arrays have been shown to be viable for low-light-level imaging applications. Noise levels of a few hundred electrons per sample have been measured at room temperature and with conventional MOS on-chip preamplifiers. Cooled arrays with improved preamplifiers appear to be capable of achieving noise levels of 10 electrons per sample. The tapped CCD delay line provides a versatile analog signal processing building block for sonar, radar, and communications applications. High performance digital memory and signal processing can be achieved with CCD's at lower cost than with conventional digital techniques.

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(Continued from Page 22)

Nicholas Djeu, the program's principal investigator, reports that the laser is based on a novel concept which combines optical pumping of the upper laser level with the collisional quenching of the lower laser level using nitrogen. The new laser should attain at least 0.1 percent efficiency in the visible green region.

Optical pumping of the laser medium is obtained from a 20-Mhz electrodeless lamp coaxial with the laser tube. The laser tube itself is 3 mm in diameter and has an active length of 30 cm. The laser has the capability to convert approximately one half the light absorbed at 404.7 nm to a laser output of 546.1 nm.

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Automated Weather Station

Ocean scientists at the Naval Research Laboratory (NRL) have developed a self-sustained weather sensing and transmission station. It is named PAWS for Polar Automated Weather Station. The first experimental PAWS is being prepared to begin a one-year operational test at Umiat, Alaska. During the PAWS test period, the station also might provide valuable operational weather information to aircraft associated with the construction of the Trans-Alaska Oil pipeline, the Naval Arctic Research Laboratory (NARL), and Naval Petroleum Reserve #4 oil exploration groups.

NRL developed PAWS to provide the Navy with a weather monitor of high reliability and minimum maintenance requirements for deployment in remote locations such as the open ocean and polar regions.

The PAWS is powered by a radio isotope power generator (RPG) and can communicate on two frequencies in the HF band. An automated central station located at NARL, Barrow, Alaska, will be used to interrogate and monitor the PAWS.

Navy Lab Recycles Pollutant to Valuable Commodity

A method to convert a pollutant by-product of TNT manufacture to a valuable chemical product has been developed at the White Oak Laboratory of the Naval Surface Weapons Center in Silver Spring, Maryland. This product, nitroform, is required for high-energy missile propellants. Prior to this development the cost of nitroform was high, and its availability limited and erratic.

Tetranitromethane (TNM), a precursor to nitroform, is discharged into the air during the manufacture of TNT and is considered an air pollutant. Drs. W. H. Gilligan and T. N. Hall of the White Oak Laboratory, in cooperation with Dr. W. T. Bolleter of the Army's Radford Ammunition Plant in Virginia, and Dr. Everett Gilbert of Picatinny Arsenal in New Jersey, developed a process to remove TNM from ammunition manufacture exhaust gases, thereby eliminating this source of air pollution.

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The Radford Army Ammunition Plant, a major manufacturer of TNT, was requested by the Environmental Protection Agency to improve the TNT manufacturing process so that TNM would be removed from manufacturing exhaust gases. Scientists at White Oak and the Army's Picatinny Arsenal thought that if nitroform could be extracted during the TNT manufacturing process, a valuable intermediate product could be obtained, and a proposal was made to determine the feasibility of doing so. Funding was obtained from Picatinny Arsenal and from the Naval Ordnance Systems Command.

The tetranitromethane is removed from TNT manufacturing exhaust gases and converted to nitroform in a scrubbing tower. Good results have been obtained using alkaline hydrogen peroxide or a "homogenized" two-phase system of an organic liquid with aqueous alkali as the scrubbing solution. White Oak's experiments have demonstrated that 90% conversions are possible. In these scrubbing processes, the TNM is collected as an aqueous solution of nitroform suitable for use in the preparation of high energy propellants.

A ready source of nitroform would be most welcome. Radford Army Ammunition Plant plans to install the process and to offer nitroform for Department of Defense use. The plant will be able to produce several hundred thousand pounds per year, and the potential output from all TNT manufacturing plants could approach several million pounds per year.

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Basic research on the behavior of sharks will lead to more effective anti-shark hardware and better advice to people on how to avoid encounters with sharks.

Charge-Coupled Device Applications.....W. D. BAKER 22
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Charge coupling is a significant concept because it provides improved performance in terms of dynamic range, sensitivity, noise, power and weight compared to other semiconductor technology.

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Cover Caption

The gray reef shark, Carcharhinus amblyrhynchos, *an aggressive Indo-Pacific species about six feet long, is responsible for a number of attacks on underwater personnel (diver in mobile protective cage in background). Ultrasonic telemetry is presently being used to determine home ranges and day-night behavior patterns of this shark at Rangiroa, French Polynesia (photo by R. Johnson). See page 1.*

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